Light σ-Meson Production in Excited Υ Decay Processes I — Analyses —

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We analyze the $\pi\pi$ production amplitudes in the excited Υ decay processes, $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$, $\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$ and $\Upsilon(3S) \to \Upsilon(2S)\pi^+\pi^-$, and the $\pi\pi$ and $K\bar{K}$ production amplitudes in the charmonium decay processes, $\psi(2S) \to J/\psi\pi^+\pi^-$ and $J/\psi \to \phi\pi^+\pi^-$, ϕK^+K^-. The amplitudes are parametrized by the sum of Breit-Wigner amplitudes for the σ and the other relevant particles and of the direct 2π-production amplitude, following the VMW method. All the $\pi\pi$ (and $K\bar{K}$) invariant mass spectra are reproduced well with the σ Breit-Wigner amplitude by using the common parameters, $m_\sigma = 526^{+48}_{-37}$MeV and $\Gamma_\sigma = 301^{+145}_{-100}$MeV, which is almost consistent with the values obtained in our previous phase shift analyses. This strongly suggests the existence of light σ-meson.

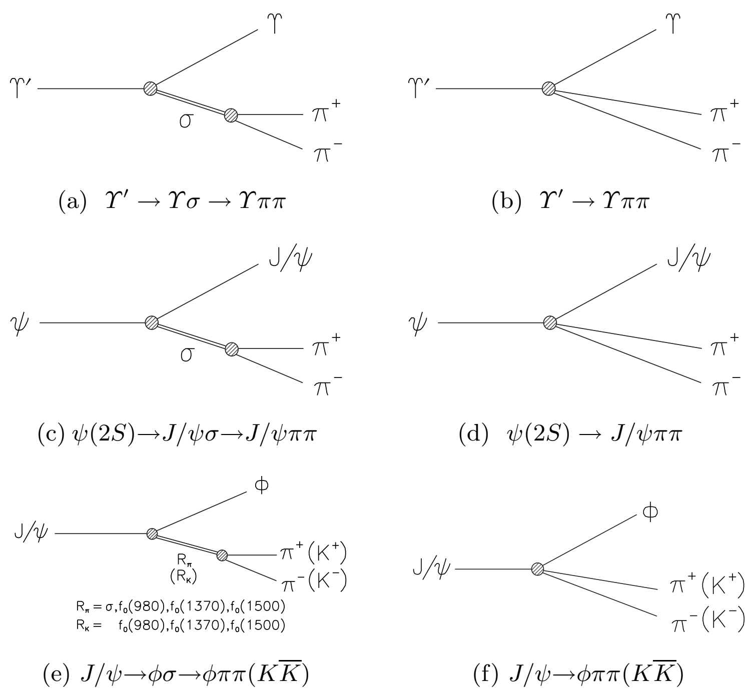
§1. Introduction

The σ-meson is a chiral partner of π-meson, and it is theoretically important from the viewpoint of chiral symmetry breaking. However, its existence had been neglected phenomenologically, mainly being based on the negative result of the analyses of $I = 0$ S-wave $\pi\pi$ scattering phase shift.

In most of the $\pi\pi$-production experiments, a large event concentration or a bump structure in the spectra of $\pi\pi$ invariant mass $m_{\pi\pi}$ around 500 MeV had been observed, however, conventionally it was not regarded as σ-resonance, but as a mere $\pi\pi$-background, under influence of the so callled "universality argument." [1] In this argument, it is stated that because of the unitarity of S-matrix and of the analyticity of the amplitudes, the $\pi\pi$ production amplitude $\mathcal{F}$ takes the form $\mathcal{F} = \alpha(s)\mathcal{T}$ ($\mathcal{T}$ being $\pi\pi$ scattering amplitude), with a slowly varying real function $\alpha(s)$. The pole position of S-matrix is determined solely through the analysis of $\mathcal{T}$, which was believed to have no light σ-pole at that time.

Recently the data of $\pi\pi$-scattering phase shift have been reanalyzed by many groups [2] including ours [3] and the existence of light $\sigma(400 \sim 700)$ is strongly suggested. The result of no σ-existence in the conventional analyses is pointed out [4] to be due to the lack of consideration on the cancellation mechanism guaranteed by chiral symmetry, and shown to be not correct. Furthermore, we have pointed out that the "universality argument" should be revised, taking into account the quark physical picture. [5] Actually the "effective" $\alpha(s)(\equiv \mathcal{F}/\mathcal{T})$, thus corrected, is not a slowly varying function but rapidly varying function even with real poles.

Now the many $\pi\pi$-production experiments must be reanalyzed independently from $\mathcal{T}$ by including the effect of direct σ-production. We parametrize $\mathcal{F}$ as a sum



(a) $\Upsilon' \to \Upsilon\sigma \to \Upsilon\pi\pi$ (b) $\Upsilon' \to \Upsilon\pi\pi$

(c) $\psi(2S) \to J/\psi\sigma \to J/\psi\pi\pi$ (d) $\psi(2S) \to J/\psi\pi\pi$

(e) $J/\psi \to \phi\sigma \to \phi\pi\pi(K\overline{K})$ (f) $J/\psi \to \phi\pi\pi(K\overline{K})$

Fig. 1. Mechanism of the relevant decays of the excited $\Upsilon(3S,2S)$, $\psi(2S)$ and the J/ψ.

of Breit-Wigner amplitudes for the relevant resonances (including σ-resonance) and of the direct 2π production amplitude, following VMW-method. This method is consistent with the requirement from S-matrix unitarity and from analyticity. The VMW method had already been applied [6] to the pp-central collision, $pp \to pp\pi\pi$, the $J/\psi \to \omega\pi\pi$ decay and the $p\bar{p} \to 3\pi^0$ annihilation. [7] The large event concentration in low $m_{\pi\pi}$ region is explained by σ-production. Here we apply this method to the analyses of the hadronic decays of excited Υ, $\Upsilon(2S,3S)$, and $\psi(1S,2S)$.

§2. Method of the analyses

We analyze the $m_{\pi\pi}$ spectra of the processes, $\Upsilon(2S) \to \Upsilon(1S)\pi^+\pi^-$, [8)-11)] $\Upsilon(3S) \to \Upsilon(1S)\pi^+\pi^-$, [11] $\Upsilon(3S) \to \Upsilon(2S)\pi^+\pi^-$ [11] and $\psi(2S) \to J/\psi\pi^+\pi^-$ [12] following the VMW method in one-channel form. The $\mathcal{F}$ is given by a coherent sum of σ-Breit-Wigner amplitude and of direct 2π-production amplitude as

$$\mathcal{F} = \frac{e^{i\theta_\sigma} r_\sigma}{m_\sigma^2 - s - i\sqrt{s}\Gamma_\sigma(s)} + r_{2\pi} e^{i\theta_{2\pi}}; \quad \Gamma_\sigma(s) = \frac{g_\sigma^2 p_1(s)}{8\pi s}, \quad p_1(s) = \sqrt{\frac{s}{4} - m_\pi^2},$$

where $r_\sigma(r_{2\pi})$ is the $\sigma(2\pi)$ production coupling and $\theta_\sigma(\theta_{2\pi})$ corresponds to the production phase. These parameters are process-dependent. The corresponding decay mechanism is depicted in Fig. 1(a), (b) for Υ decay and (c),(d) for $\psi(2S)$ decay.

The $J/\psi \to \phi\pi^+\pi^-$, ϕK^+K^- process [13] is analyzed by VMW-method in two-

channel form, where the $\pi\pi$ and KK production amplitudes, $\mathcal{F}_{\pi\pi}$ and $\mathcal{F}_{KK}$, respectively, are given by

$$\mathcal{F}_{\pi\pi} = \frac{e^{i\theta_\sigma} r_\sigma}{m_\sigma^2 - s - i\sqrt{s}\Gamma_\sigma(s)} + \sum_{f_0} \frac{e^{i\theta_{f_0}} r_{f_0} g_{f_0\pi\pi}}{m_{f_0}^2 - s - i\sqrt{s}\Gamma_{f_0}^{\rm tot}(s)} + r_{2\pi} e^{i\theta_{2\pi}};$$

$$\mathcal{F}_{KK} = \sum_{f_0} \frac{e^{i\theta_{f_0}} r_{f_0} g_{f_0 KK}}{m_{f_0}^2 - s - i\sqrt{s}\Gamma_{f_0}^{\rm tot}(s)} + r_{2K} e^{i\theta_{2K}}; \quad f_0 = f_0(980),\ f_0(1370),\ f_0(1500)$$

$$\Gamma_{f_0}^{\rm tot} = \Gamma_{f_0}^{\pi\pi} + \Gamma_{f_0}^{KK} = \frac{p_1 g_{f_0\pi\pi}^2}{8\pi s} + \frac{p_2 g_{f_0 KK}^2}{8\pi s}.$$

The corresponding decay mechanism is shown in Fig.1 (e),(f).

By using the above formulas of production amplitudes the $m_{\pi\pi}$ or m_{KK} spectra (that is, $\sqrt{s}$ spectra) are given by

$$\frac{d\sigma}{d\sqrt{s}} = \frac{p(M'^2; M, \sqrt{s}) p_1(s)}{32\pi^3 M'^2} |\mathcal{F}|^2, \quad p(M'^2; M, \sqrt{s}) = \frac{\sqrt{(M'^2 - M^2 - s)^2 - 4M^2 s}}{2\sqrt{s}},$$

where $M'(M)$ is the mass of the initial (final) quarkonium.

All the relevant spectra are fitted by using common values of the parameters, the mass of σ m_σ and the $\sigma\pi\pi$ coupling $g_{\sigma\pi\pi}$.

Table I. Values of mass and width of resonances: m_σ and $g_{\sigma\pi\pi}$ are taken to be common through all the processes. The other resonance paramaters are relevant only in the $J/\psi \to \phi\pi\pi,\ \phi KK$ process. Mass and coupling constant of $f_0(980)$ fall, respectively, on lower and upper limits in the fit.

	m_α/MeV	$g_{\alpha\pi\pi}$/GeV	$\Gamma_{\alpha\pi\pi}$/MeV	$g_{\alpha KK}$/GeV	$\Gamma_{\alpha KK}$/MeV
σ	526	3.06	301		
$f_0(980)$	966	1.77	62	2.70	10
$f_0(1370)$	1402	2.81	109	0.74	5
$f_0(1500)$	1498	2.08	57	1.89	36

Table II. Production couplings r_σ, $r_{2\pi}$ and phase θ_σ in one channel formula. θ_σ is set to be zero and only the relative ratios of r are meaningful.

	$\Upsilon(2S \to 1S)$	$\Upsilon(3S \to 1S)$	$\Upsilon(3S \to 2S)$	$\psi(2S \to 1S)$
r_σ	6031	103	3138	659
$r_{2\pi}$	38512	1381	21270	2986
$\theta_{2\pi}$	197	322	154	199

Table III. Production couplings r_σ, $r_{2\pi}$ and phase θ_σ in two channel formula of the decay $J/\psi \to \phi\pi\pi,\ \phi KK$. θ_σ is set to be zero and only the relative ratios of r are meaningful.

	σ	$f_0(980)$	$f_0(1370)$	$f_0(1500)$	2π	$2K$
r	41GeV^2	42GeV	127GeV	78GeV	195	238
θ(degree)	0(fixed)	355	104	329	382	56

§3. Results and Conclusion

The results of our analysis are shown in Fig. 2. The spectra of five different processes ((a) to (e) in Fig. 1) are reproduced well by the interference between the

Table IV. χ^2 values for the respective data sets. Total χ^2 is $\chi^2/(N_{\rm data}-N_{\rm param}) = 86.5/(150-37)$.

	$\Upsilon(2S \to 1S)$ CLEO [8]	$\Upsilon(2S \to 1S)$ CLEO [9]	$\Upsilon(2S \to 1S)$ CLEO [10]	$\Upsilon(2S \to 1S)$ CLEO [11]
$N_{\rm data}$	14	10	14	10
χ^2	27.0	4.8	6.8	8.9
	$\Upsilon(3S \to 1S)$ CLEO [8]	$\Upsilon(3S \to 2S)$ CLEO [8]	$\psi(2S \to 1S)$ Crystal Ball [12]	$J/\psi \to \phi\pi\pi,\ \phi KK$ MARK II [13]
$N_{\rm data}$	15	11	26	26+24
χ^2	9.8	3.4	3.3	16.7+16.7

σ Breit-Wigner amplitude with

$$m_\sigma = 526^{+48}_{-37} \quad \text{MeV}, \quad \mathit{\Gamma}_\sigma = 301^{+145}_{-100} \quad \text{MeV} \tag{3·1}$$

and the direct 2π production amplitude. The total χ^2 is $\chi^2/(N_{\rm data} - N_{\rm param}) = 86.5/(150-37) = 0.77$. The contribution of σ and of direct 2π production amplitudes to the spectra are given, respectively, by dot and dot-dashed lines in this figure. It is notable that the destructive interference between σ amplitude and 2π amplitudes explains the suppression of the spectra in the threshold region of $\Upsilon(2S \to 1S)$ and $\psi(2S \to 1S)$ decays, while in $\Upsilon(3S \to 1S)$ decay these two amplitudes interfere constructively, and the steep increase from the threshold is reproduced. These threshold behaviors of the production amplitudes are[4] shown to be consistent with the restriction from chiral symmetry. The double peak structure is also reproduced well by the above interference, that is, the destructive interference around the σ-peak position.

The obtained values of parameters are given in Table I for masses and widths of resonances and in Table II(III) for production couplings and phases in one channel (two channel) formula. The χ^2 values for respective data sets are given in Table IV.

The property of σ, given in Eq.(3·1) is almost consistent with the results obtained in our previous $\pi\pi$ phase shift analysis,[3] m_σ=535$\sim$675MeV and $\mathit{\Gamma}_\sigma$=385$\pm$70MeV. These results give strong evidence for existence of the light σ(500–600).

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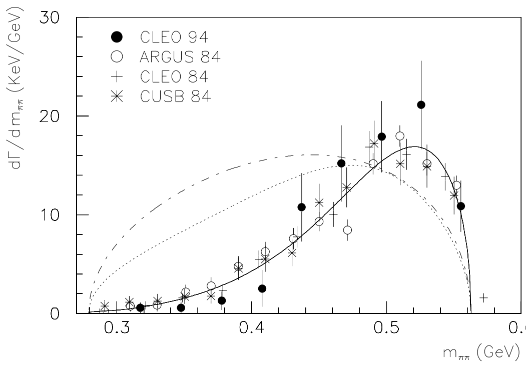
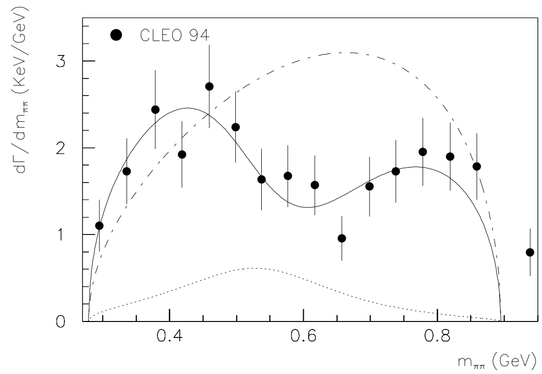
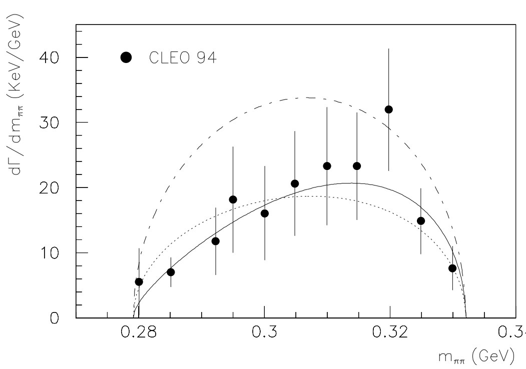


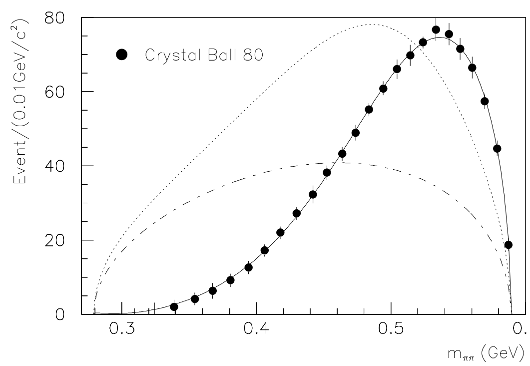
(a) $\Upsilon(2S) \to \Upsilon(1S)\pi\pi$



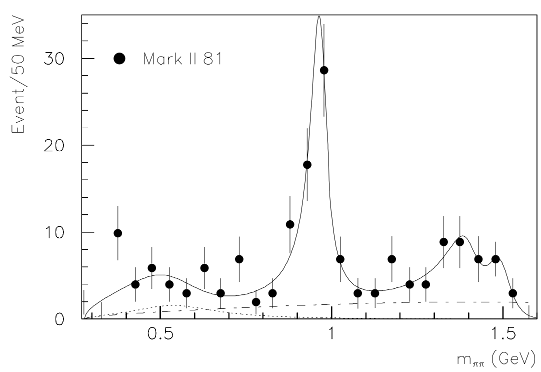
(b) $\Upsilon(3S) \to \Upsilon(1S)\pi\pi$



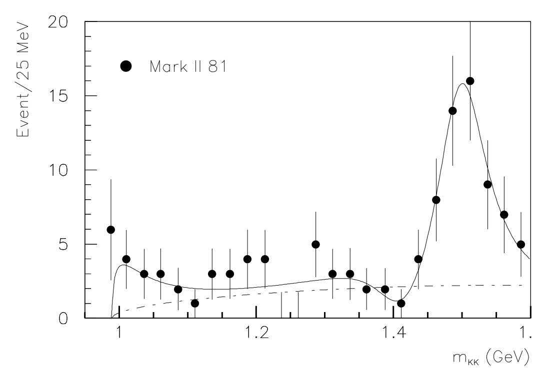
(c) $\Upsilon(3S) \to \Upsilon(2S)\pi\pi$



(d) $\psi(2S) \to J/\psi\pi\pi$



(e) $J/\psi \to \phi\pi\pi$



(f) $J/\psi \to \phi KK$

Fig. 2. The result of the fit to the $\pi\pi$ (or KK) mass spectra of (a) $\Upsilon(2S) \to \Upsilon(1S)\pi\pi$, (b) $\Upsilon(3S) \to \Upsilon(1S)\pi\pi$, (c) $\Upsilon(3S) \to \Upsilon(2S)\pi\pi$, (d) $\psi(2S) \to J/\psi\pi\pi$, (e) $J/\psi \to \phi\pi\pi$, and (f) $J/\psi \to \phi KK$. The bold line represents the fit, while the dotted (dot-dashed) does the contribution of σ(direct 2π)-production. By multiplying appropriate proportional factors, the different data sets are adjusted to the one with the largest number of events. In (a) CLEO data [8], shown by black circle, with factor 1; ARGUS [9] by open circle with factor 1.5; CLEO [10] by cross with factor 2; CUSB [11] by asterisk with factor 3. Data in (b), (c) and (d) are respectively, from CLEO [8], CLEO [8] and Crystal Ball [12]. Data in (e) and (f) are from MARK II [13].